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FOREWORD

Part of this report was written at the Department of Mathematics, Monash University, Clayton, Victoria 3168, Australia, and part during tenure of an NRC-NASA Resident Research Associateship at the Jet Propulsion Laboratory. A longer version of this report is being published in the <u>Proceedings of the Astronomical Society of Australia</u> (1981).

ABSTRACT

Following observations made by Voyager 1 at Saturn last November 1980, as well as observations from the two Voyager encounters at Jupiter, a unified model for the formation of regular satellite systems and the planetary system is outlined. The basis for this modern Laplacian theory is that there existed a large supersonic turbulent stress arising from overshooting convective motions within the three primitive gaseous clouds which formed Jupiter, Saturn and the sun. Calculations show that if each cloud possessed the same fraction of supersonic turbulent energy, equal to about 5% of the cloud's gravitational potential energy, then the broad mass distribution and chemistry of all regular satellite and planetary systems can be simultaneously accounted for. Titan is probably a captured moon of Saturn. Several predictions about observations that are to be made by Voyager 2 at Saturn on August 25, 1981 are presented.

CONTENTS

1. INTRODUCTION

One of the surprising discoveries to emerge from the Voyager 1 fly-by of Saturn was the non-uniform distribution of mean densities observed amongst its inner satellites[1,2]. Some pre-Voyager ideas of satellite formation[3-5] indicated that the densities might have increased steadily towards the planet, with rocky moons nearest the center, as is the case in both the Jovian and planetary systems. Instead, Voyager 1 found that the densities of Mimas, Dione and Rhea all lie close to the value 1.3 g cm^{-3} expected for a body consisting of solar abundance proportions of about 40% chondritic rock and 60% H_2O ice[6], whilst Enceladus and Tethys appear to contain more ice than is expected on the basis of solar abundances. In this publication I wish to report the results of calculations, based on the modern Laplacian theory for the origin of the solar system[7,8], which indicate that if each of the primitive gaseous clouds which formed Jupiter, Saturn and the sun possessed a common proportion of supersonic turbulent kinetic energy, equal to about 5% of the cloud's gravitational potential energy, then the broad mass distribution and chemistry of all regular satellite and planetary systems can be simultaneously accounted for. I suggest that the anomalously low densities reported for Tethys and Enceladus are due to uncertainties in the knowledge of satellite masses.

2. THE MODERN LAPLACIAN THEORY

According to the modern Laplacian theory for the formation of the solar system, the planets/regular satellites condensed from a concentric system of orbiting gaseous rings which were shed by the primitive gaseous envelopes which gravitationally contracted to form each central body. The orbital radii R_n of these rings of mass m_n, numbering inwards from

the outermost one ($n = 0,1,2,\ldots$), are related to each other by the equations

$$R_n/R_{n+1} = [1 + m_{n+1}/M_{n+1}f]^2 \qquad (1)$$

where $M_n \gg m_n$ and f denote the mass and moment-of-inertia factor of the parent cloud. This quantity measures the relative spatial distribution of mass within the cloud and is sensitive to the amount of supersonic turbulent stress, given by $\langle\rho_t v_t^2\rangle = \beta\rho GM(r)/r$, where $\rho = \rho(r)$ is the gas density, $M(r)$ the mass interior to radius r, and $\beta \sim 0.1$ is the so-called turbulence parameter[9]. The turbulent stress is typically 100 times larger than the usual gas pressure $\rho\mathcal{R}T/\mu$ at the photosurface of the cloud and implies the existence of turbulent velocities having magnitude of order 100 km s^{-1} for a cloud of solar mass and radius 3 $R_\odot$. This value coincides with the magnitudes that are observed at the surfaces of T Tauri stars, as discussed by Cohen at the recent Portuguese workshop on young stars[10]. In fact, the basic assumption of the modern Laplacian theory, that there exists a reservoir of powerful convective motions within the interior of a young gravitationally contracting cloud, is drawn from the observation of the huge flux of mechanical energy which emanates from T Tauri stars. I have proposed[9] that this flux is caused by overshooting convective elements which cross the visible photosurface at supersonic speeds then decelerate to rest in the outer transparent layers of the star, before returning in the form of a stable subsonic downwind.

Turbulent stress greatly expands the outer tenuous layers of the cloud, causing f to sharply fall and the cloud to appear very centrally condensed. Typically, $f \simeq 0.01 - 0.02$. The contracting cloud is then able to give up its excess spin angular momentum at the expense of

shedding very little mass. Such a result is necessary if we are to account for the low masses of the planetary and regular satellite systems, relative to their primaries. In the case of the planetary system, where $\langle R_n/R_{n+1}\rangle = 1.723$, the mean ring mass is seen to be $0.003\ M_\odot$, taking $f = 0.01$. From Table 1 it follows that such a mass of gas contains a total of $15\ M_\oplus$ of condensable rocks and ices, which is precisely comparable with the masses of the icy planets Uranus and Neptune. The first stage in the formation of the major planets is the settling out and accumulation of the various condensates along the mean orbit of each gas ring to form a compact planetary core of mass $\sim 10 - 15\ M_\oplus$. The existence of such cores has been confirmed by a wide range of planetary model calculations[11-13] and spacecraft gravity data[14]. Whilst these planetary cores are accumulating, much of the gas of the outer rings is lost through thermal evaporation of the more energetic molecules[15]. The second stage in major planet formation is the capture of the residual gases of each ring by the planetary cores to form the rotating convective envelopes from which each of the regular satellite systems are, in turn, formed.

To account for the shortfall in the masses of the terrestrial planets from the value $m_{rock} \simeq 5\ M_\oplus$ predicted by equation (1) and Table 1, it is necessary to assume that a large fraction of the rocky condensate remained suspended in the gas as a fine dust. This dust would later be swept away with the gas when the protosun passed through its overluminous phase at equatorial size $R_e \sim 35\ R_\odot$, with the luminosity rising to $50\mathscr{L}_\odot$. Strong thermal stirring breaks down the angular velocity distribution which is responsible for the gas ring structure and causes the gas to disperse away from the mean orbit R_n.

The mass distribution of the Galilean moons suggest that each of these bodies condensed from gaseous rings of roughly comparable mass[16]. Voyager data show that both Europa[17] and Callisto[18] contain the same mass of rock $\sim 5 \times 10^{25}$ g equal to the value given by equation (1) for $f = 0.02$, taking $M = M_J = 1.9 \times 10^{30}$ g and assuming that the gas has solar composition. The fact that Io and Ganymede have a comparable but larger mass of rock suggests, however, that the actual heavy element mass fraction Z_J of the protojovian cloud may have exceeded the solar value $Z_{\odot} \approx 0.018$ by some 80%. That Z_J and $Z_{\odot}$ can differ is understandable. On the one hand, the process of core formation within the gas ring shed by the protosun at Jupiter's orbit causes Z_J to decline. On the other hand, thermal evaporation of the uncondensed gases from this ring leads to a subsequent enhancement of the relative mass fraction of suspended solids.

The masses of Saturn's inner moons are much smaller than the available mass of rock $\sim 8 \times 10^{24}$ g per gas ring based on equation (1), assuming $Z_S = Z_{\odot}$ and taking $M = M_S$, $f = 0.02$. Comparing this situation with the case of the terrestrial planets, it was argued[3] that Mimas through Dione would be mostly rocky. Calculations[4,5] of the temperature T_n of each gas ring for the case $f = 0.02$ supported this conclusion, especially in view of the relation $T_n \propto R_n^{-1}$ characteristic of uniform gravitational contraction, which favors progressively higher temperatures amongst the innermost rings. Only Rhea was predicted to condense below the H_2O ice-point and have a density of 1.3 g cm^{-3}.

3. POST-VOYAGER 1 CALCULATIONS

Following Voyager 1's discovery that all of the moons Mimas through Rhea were low density objects, it became clear that the surface temperatures of the real protosaturnian cloud were much less than the values defined by the turbulent polytropic model having $f = 0.02$, where $\beta = 0.081$. A new series of cloud models was therefore constructed which had a greater amount of turbulent stress and correspondingly lower surface temperatures. The construction of these models is described in more detail elsewhere[7,8]. The minimum value of β needed to ensure that Mimas condenses below the H_2O ice-point is found to be $\beta_{min} = 0.105$. This bound lies close to the value $\beta_J = 0.109$ which describes[16] the chemistry of the Jovian system for a cloud having helium mass fraction $Y = 0.25$. With $Y = 0.20$, the value measured by Voyager [19], the cloud is less dense and cooler. The condition that Io condense within the stability field of FeS whilst Ganymede condense below the H_2O ice-point is found to be $0.102 \lesssim \beta_J \lesssim 0.108$. These calculations suggest that the chemistry of the Jovian and Saturnian systems, as well as possibly the planetary system, can be accounted for with a single choice of β lying in the interval $0.105 \lesssim \beta \lesssim 0.108$. That is, it is the value of β, rather than f, which characterizes the common structure of the three clouds. The latter quantity depends on the fraction of dissociated H_2 as well as β, and this varies from one cloud to the next as a result of their different masses M. The parameter β, however, is independent of the atomic state of the gas. Physically, $\frac{1}{2}\beta$ is the fraction of the local gravitational potential energy density $\rho GM(r)/r$ which is stored as kinetic energy $\frac{1}{2}\langle\rho_t v_t^2\rangle$ in non-thermal turbulent convective motions.

To test the hypothesis of a universal value of β, cloud models were constructed for the case $\beta = 0.1065$. The surface temperature T_e of each such model is plotted in Fig. 1 against cloud size R_e. The dashed lines in the Figure are the condensation temperatures of major chemical species at the clouds' equators, computed from the equilibrium condensation data of Lewis[20]. For large R_e, the gravitational contraction is assumed to be uniform and T_e behaves closely as A_e/R_e, apart from modest changes due to the dissociation of H_2. The constants of proportionality A_e are computed from the condition that the ratio R_n/R_{n+1}, of the orbital radii R_n of successively disposed gas rings, matches the observed mean value. In the final stages of contraction, commencing at transition radii $3R_S$, $3R_J$ and $22\ R_\odot$ respectively, the turbulence is progressively reduced and temperature profiles are matched such that each cloud preserves its moment-of-inertia factor f, equal to the value $f_\star$ at the transition radius. The values of $f_\star$ for the three clouds protosaturn, protojupiter and protosun are 0.007, 0.015 and 0.029, respectively. As β declines, the spacing between newly shed rings decreases. Choosing final values of T_e at $R_e = 1.5\ R_p$ of 235 K, 850 K and 3500 K, ring shedding ceases altogether at the edge of the A ring ($2.27\ R_S$), $2.1\ R_J$ and $5\ R_\odot$ respectively. Gas rings are shed at the positions of Amalthea, the co-orbital moons S10 and S11, and the F ring ($R_e = 2.32\ R_S$). In Table II, we have listed the temperature, density and pressure of each gas ring at the moment of detachment from the parent cloud, supposing that a ring was shed at the present orbits of each of the planets/satellites. We observe that the sequence of planetary compositions implied by the protosolar temperature locus very accurately reproduces the observed[20] chemistry of the terrestrial planets. No planet can form

inside the orbit of Mercury simply because the temperature is too high for the condensation of any chemical species. The temperature at the Earth's orbit lies just above the condensation point of the hydrated silicate tremolite. Condensation of this mineral does, however, occur in the outer 10% of the mass of the gas ring centered on this orbit. This leads to an estimate for the Earth's water content of $3 \times 10^{-4}\ M_{\oplus}$, which is close to the observed value. Direct condensation of H_2O does not occur until the orbit of Jupiter, confirming the view that the separation between the minor and major planets was determined by the first appearance of this species.

The broad chemistry of the four Galilean moons emerges naturally from Fig. 1. Petrological studies[17] of Europa indicate that the icy surface of this moon formed from water released from hydrated silicates[16], rather than water which condensed directly from a Jovian nebula. Loss of volatiles through accretionary heating is probably responsible for the ice mass fractions of Ganymede and Callisto being below solar abundance.

Protosaturn is the coolest and most centrally condensed ($f_S = 0.007$) of the three clouds since it is the least massive and its hydrogen is almost entirely molecular. To account for the mass of Rhea it is necessary to take $Z_S = 0.3\ Z_{\odot}$. The steady decline in the masses of the moons interior to the orbit of Rhea is probably due to a destructive mixing between the closely spaced gas rings. Satellite growth takes place only as long as the ring remains intact[21].

4. TITAN AND OTHER ANOMALIES OF THE SATURNIAN SYSTEM

Titan's mass is 60 times too large to be accounted for by equation (1). Moreover, had it condensed from the protosaturnian cloud, one would expect an atmospheric composition dominated by CH_4, rather than the N_2 observed by Voyager 1. It therefore seems more likely, as first put forward by Prentice[5], that Titan condensed as a secondary embryo within the gas ring that was shed by the protosun at Saturn's orbit, and was later captured by the protosaturnian cloud after the latter had contracted to a size smaller than Titan's present orbit. The absence of any moons between Rhea and Titan, at the positions indicated in Fig. 1, supports this conjecture of a cataclysmic origin. If Titan is a captured moon, then the close similarity of its density with that of Ganymede and Callisto suggests that complete thermochemical equilibrium was attained in the outer layers of the protosolar cloud, as originally assumed by Lewis[20] (cf. ref. 22). Perhaps Iapetus, which has a size very similar to Rhea, once occupied an orbit between Rhea and Titan and was driven out during Titan's capture. In that case, we expect its density to be 1.3 g cm^{-3}. The anomalously low Tethys density of 1.0 ± 0.1 g cm^{-3} found by Voyager 1 draws attention to the importance of the forthcoming Voyager 2 measurement of this satellite's mass. The presently accepted mass is inferred by indirect means[23] and, on the basis of Fig. 1, may be underestimated by some 20%. Lastly, we observe from Fig. 1 that the irregularly shaped moons S10 and S11 (i.e., 1980 S1 and 1980 S3), as well as other small moonlets S13, S14 and S15 (or 1980 S26, 27, 28) which condense from gas rings shed at the orbit of the F ring and the edge of the A ring, should consist mostly of serpentined rock

and have a density close to 2.4 g cm^{-3}. These moons should therefore all have low albedos and be irregular in shape[5].

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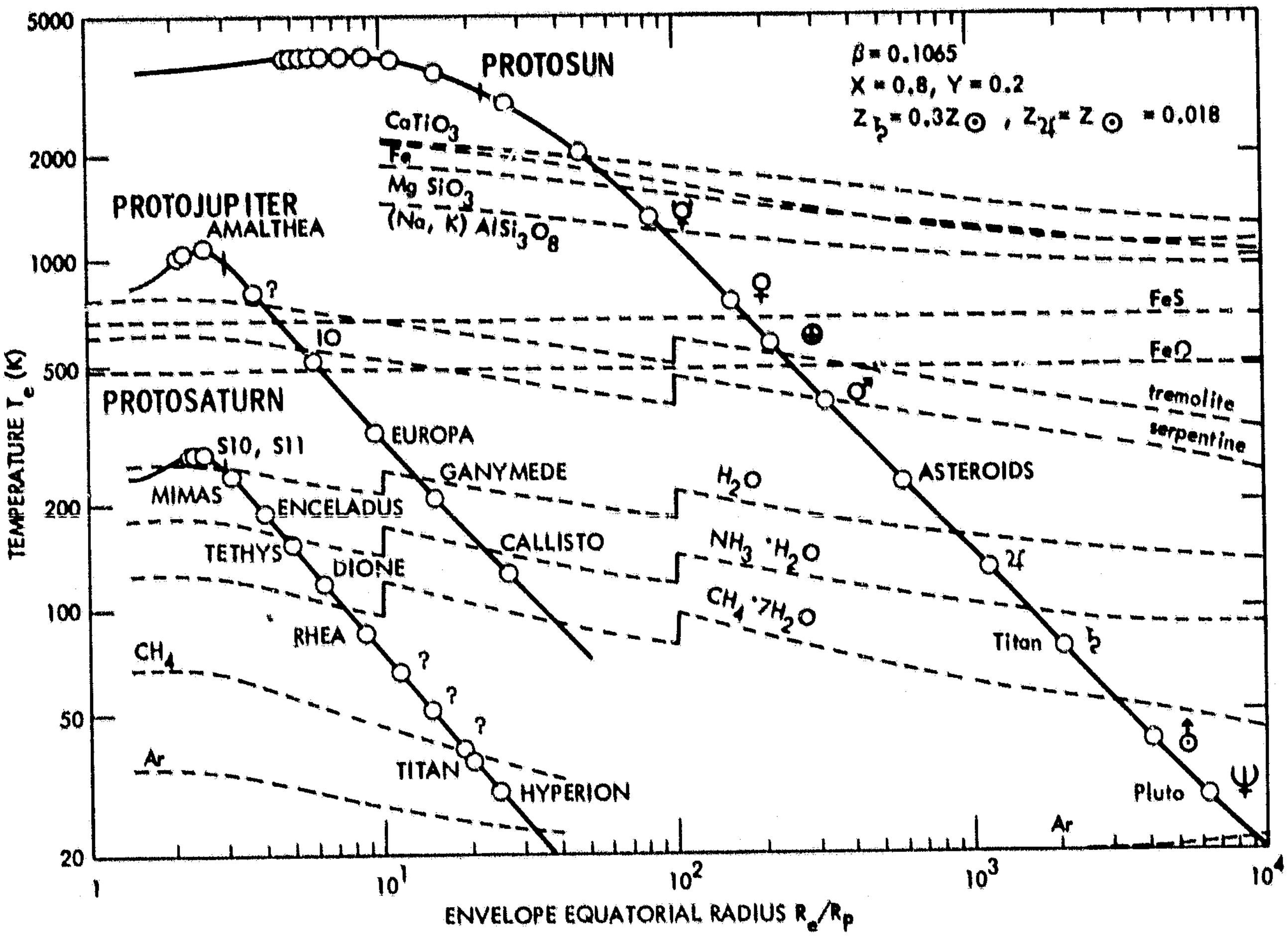

Fig. 1. Surface temperatures T_e of the primitive turbulent gaseous clouds which contracted to form Saturn, Jupiter and the sun, plotted as the solid lines, versus equatorial size R_e, which is expressed in units of the present equatorial radii R_p. Each cloud has the same H and He mass fractions, X and Y respectively, and the same relative fraction of supersonic turbulent kinetic energy, measured by the parameter β, which is defined in the text. The broken curves define the equilibrium condensation temperatures of the major chemical species, derived from the data of Lewis[20].

Table I. Cumulative abundances of major condensing chemical species in solar material.

Chemical species	Mass fraction
Anhydrous chondritic rock [$CaTiO_3$, $MgSiO_3$, $(Na,K)AlSi_3O_8$, FeO, NiO]	0.005
above + H_2O ice	0.013
above + NH_3 (as $NH_3 \cdot H_2O$ ice)	0.014
above + CH_4 (as $CH_4 \cdot 7H_2O$ ice)	0.015

Table II. Physical characteristics and condensing chemical constituents of the system of gaseous rings shed by the primitive turbulent ($\beta = 0.1065$) clouds of Saturn, Jupiter and the sun.

Satellite	Orbit radius R_n/R_p	Gas ring temperature T_n(K)	Gas ring density ρ_n(g cm^{-3})	Gas pressure (bar)	Chemical condensate
		PROTOSATURNIAN CLOUD			
		$[M_S = 5.69 \times 10^{29}$ g, $R_S = 6.033 \times 10^9$ cm$]$			
S13, S14	2.32	275	8.8(-4)	9.0	hydrated silicates
S10, S11	2.51	274	8.2(-4)	8.4	hydrated silicates
Mimas	3.08	242	5.4(-4)	4.9	anhydrous rock + H_2O ice
Enceladus	3.98	187	2.5(-4)	1.7	anhydrous rock + H_2O ice
Tethys	4.92	151	1.3(-4)	7.4(-1)	above + $NH_3 \cdot H_2O$ ice
Dione	6.28	118	6.3(-5)	2.8(-1)	above
Rhea	8.75	85	2.3(-5)	7.4(-2)	above + $CH_4 \cdot 7H_2O$ ice
		PROTOJOVIAN CLOUD			
		$[M_J = 1.901 \times 10^{30}$ g, $R_J = 7.14 \times 10^9$ cm$]$			
Amalthea	2.54	1090	4.3(-3)	1.7(2)	anhydrous silicates + Fe, Ni
?	3.70	810	1.7(-3)	5.0(1)	anhydrous silicates + Fe, Ni
Io	5.91	510	4.1(-4)	7.7	above + FeS + tremolite
Europa	9.40	320	1.0(-4)	1.2	above + FeO(FeS+FeO) + serpentine
Ganymede	14.99	207	2.4(-5)	1.8(-1)	anhydrous rock + H_2O ice
Callisto	26.33	126	3.9(-6)	1.9(-2)	above + $NH_3 \cdot H_2O$ ice
		PROTOSOLAR CLOUD			
		$[M_\odot = 1.989 \times 10^{33}$ g, $R_\odot = 6.96 \times 10^{10}$ cm$]$			
'Vulcan'	48.3	2010	5.6(-6)	4.2(-1)	---
Mercury	83.2	1315	8.3(-7)	4.1(-2)	$CaTiO_3$,Fe,Ni,$MgSiO_3$
Venus	155	750	9.2(-8)	2.6(-3)	above + (Na,K)$AlSi_3O_8$
Earth	215	560	2.9(-8)	6.1(-4)	above + FeS(+ tremolite)
Mars	328	383	6.5(-9)	9.3(-5)	above + FeO(FeS+FeO) + serpentine
Asteroids	595	225	8.0(-10)	6.7(-6)	above
Jupiter	1118	128	8.8(-11)	4.2(-7)	anhydrous rock + H_2O ice
Saturn (Titan)	2050	75	1.1(-11)	3.0(-8)	above + $NH_3 \cdot H_2O$ ice
Uranus	4122	41	9.6(-13)	1.5(-9)	above + $CH_4 \cdot 7H_2O$ ice
Neptune (Pluto)	6463	28	2.1(-13)	2.2(-10)	above

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